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• **Original Paper** •

Atmospheric Circulation and Dynamic Mechanism for Persistent Haze Events in the Beijing–Tianjin–Hebei Region

Ping WU[1,2,3], Yihui DING[3], and Yanju LIU*[3]

[1]*College of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing* 210044*, China*
[2]*Chinese Academy of Meteorological Sciences, Beijing* 100081*, China*
[3]*National Climate Center, Beijing* 100081*, China*

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ABSTRACT

In this study, regional persistent haze events (RPHEs) in the Beijing–Tianjin–Hebei (BTH) region were identified based on the Objective Identification Technique for Regional Extreme Events for the period 1980–2013. The formation mechanisms of the severe RPHEs were investigated with focus on the atmospheric circulation and dynamic mechanisms. Results indicated that: (1) 49 RPHEs occurred during the past 34 years. (2) The severe RPHEs could be categorized into two types according to the large-scale circulation, i.e. the zonal westerly airflow (ZWA) type and the high-pressure ridge (HPR) type. When the ZWA-type RPHEs occurred, the BTH region was controlled by near zonal westerly airflow in the mid–upper troposphere. Southwesterly winds prevailed in the lower troposphere, and near-surface wind speeds were only 1–2 m s^{-1}. Warm and humid air originating from the northwestern Pacific was transported into the region, where the relative humidity was 70% to 80%, creating favorable moisture conditions. When the HPR-type RPHEs appeared, northwesterly airflow in the mid–upper troposphere controlled the region. Westerly winds prevailed in the lower troposphere and the moisture conditions were relatively weak. (3) Descending motion in the mid-lower troposphere caused by the above two circulation types provided a crucial dynamic mechanism for the formation of the two types of RPHEs. The descending motion contributed to a reduction in the height of the planetary boundary layer (PBL), which generated an inversion in the lower troposphere. This inversion trapped the abundant pollution and moisture in the lower PBL, leading to high concentrations of pollutants.

Key words: Beijing–Tianjin–Hebei region, regional persistent haze events, atmospheric circulation, dynamic mechanism

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1. Introduction

With the rapid economic development and the acceleration of urbanization in China, air pollution has become even more serious over the past few decades (Shao et al., 2006). Moreover, persistent and heavy haze events have occurred more frequently in central and eastern China, especially in the Beijing–Tianjin–Hebei (BTH) region, the Yangtze River Delta and the Pearl River Delta (Chan and Yao, 2008; Wu et al., 2010; Ding and Liu, 2014; Wu et al., 2016). Notably, the BTH region is the most typical and the most heavily affected area (Wang et al., 2014b). In January 2013, a heavy haze/fog occurred in central and eastern China, including ten provinces and autonomous regions. Among them, the BTH region was seriously polluted. The increase in haze days not only decreases visibility (Deng et al., 2008), and influences traffic safety, but can also cause serious harm to human health (Bai et al., 2006). At present, these frequently-occurring haze events have become one of the most serious environmental problems in the BTH region, potentially hindering its economic and social development (Wang et al., 2014b). Thus, detailed studies on haze pollution weather over the BTH region are urgently needed.

Increases in pollutant emissions provide favorable conditions for the occurrence of haze, with certain meteorological conditions working as a catalyst. Wu (2011) pointed out that emitted air pollutants are the internal cause and meteorological conditions are the external cause of the occurrence of haze. If the total amount of emitted pollutants is roughly stable in a particular period, the meteorological conditions will be the determining factor for the occurrence of haze. A number of studies have shown that the likelihood of air pollutants diluting and diffusing varies according to different meteorological conditions. Atmospheric circulation, local meteorological conditions, the structure of the planetary boundary layer (PBL), and other factors have remarkable effects on the formation of haze (Kassomenos et al., 2003; Flocas

* Corresponding author: Yanju LIU
Email: liuyanj@cma.gov.cn

et al., 2009; Zhao et al., 2013; Zhang et al., 2014; Fu et al., 2014; Wang et al., 2014a, 2015). Flocas et al. (2009) analyzed the influences of four types of synoptic-scale circulation and five types of local-scale circulation on air pollution episodes in a major coastal city in Greece, and found that the conditions that caused the pollution events included the presence of an anticyclone over northern Greece, a weak surface pressure gradient intensity, a temperature increase of at least 1°C during the previous three days in the lower troposphere, and the development of a sea breeze. The circulation of the zonal westerly airflow in the mid–high latitudes, weak cold air activities, weak surface winds and high relative humidity were considered as the main causes for the heavy haze/fog event in eastern China in January 2013 (Liu et al., 2014; Wang et al., 2014a; Zhang et al., 2014). Chen and Wang (2015) pointed out that the occurrence of severe haze events in North China in boreal winter generally correlate with weakened northerly winds and the development of inversion anomalies in the lower troposphere, a weakened East Asian trough in the mid-troposphere and the East Asian jet in the upper troposphere. The different atmospheric circulation conditions in the BTH region have also been found to be the primary cause for the differences in haze weather in winter and summer in this region (Liao et al., 2014).

The PBL is the lowest part of the troposphere and plays an important role in the development of haze. The formation mechanisms of haze events have been studied by analyzing the evolutionary characteristics of PBL in recent years (Baumbach and Vogt, 2003; Quan et al., 2013; Zhao et al., 2013). The PBL height and atmospheric stability are key parameters indicating the vertical dispersion ability of air pollutants (Baumbach and Vogt, 2003; Zhang et al., 2009). A strong temperature inversion and downward air motion in the PBL allows pollutants to accumulate in a shallow layer (Zhao et al., 2013; Dai et al., 2016). Quan et al. (2013) found a positive feedback cycle for heavy pollution in megacities, where, due to the effect of haze, the heat flux decreases significantly, further depressing the development of the PBL. The repressed structure of the PBL further weakens the diffusion of pollutants, leading to heavy pollution. Thus, the evolution of the PBL should be studied in more detail.

As far as we know, most previous studies have concentrated on analyzing the basic characteristics of haze days, or the atmospheric circulation and local meteorological conditions related to a particular haze event. In contrast, the effects of atmospheric circulation on, and the dynamic mechanisms involved in, severe regional persistent haze events (RPHEs) have yet to be comprehensively investigated. In order to better understand the physical mechanisms underlying RPHE occurrence and improve the predictability of RPHEs, the present study (1) objectively identified RPHEs in the BTH region from 1980 to 2013, (2) comprehensively analyzed the associated atmospheric circulation conditions for these events, and (3) explored the dynamic mechanisms involved in the formation and maintenance of the RPHEs, with particular emphasis on the effect of the vertical motion on the PBL height and haze weather.

2. Data and methods

2.1. *Meteorological data*

The data used in this work were as follows: (1) daily data on haze, visibility, relative humidity and wind speed from 174 observation stations within the study area (Fig. 1) from 1980 to 2013, provided by the National Meteorological Information Center, China Meteorological Administration (CMA). The occurrence of a haze day was defined as a haze weather phenomenon recorded in the dataset with daily mean visibility below 10 km and daily mean relative humidity less than 90%. (2) Daily data on wind, height, vertical speed and specific humidity provided by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset from 1980 to 2013, with a horizontal resolution of $2.5° \times 2.5°$. (3) Daily PBL height data provided by the NCEP final global forecast system (FNL) reanalysis dataset from 1999 to 2013, with a horizontal resolution of $1° \times 1°$.

2.2. *Objective identification method for RPHEs in BTH region*

Ren et al. (2012) put forward the Objective Identification Technique for Regional Extreme Events (OITREE). The evolutionary process of a regional event is similar to a candied-fruit string. Each "candied fruit" is equivalent to a daily impacted area, while a complete regional event is identified when all daily impacted areas are strung together. This method has been applied to identify several types of regional extreme events and has obtained good results with respect to regional meteorological drought events, heavy precipitation events, high temperature events, and low temperature events (Gong et al., 2012; Li et al., 2014).

In this study, the OITREE method was used to identify RPHEs in the BTH region from 1980 to 2013. The specific

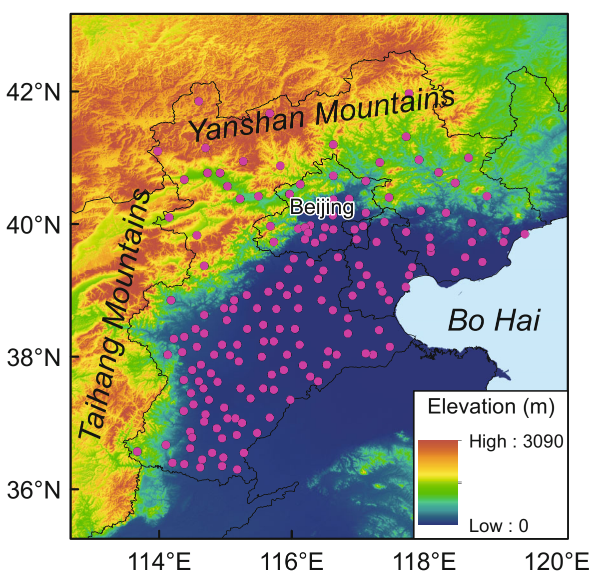

Fig. 1. Topographic map (shading; units: m) of the BTH region and the location of the meteorological sites (red dots).

identification process was as follows: (1) Define the neighboring stations for each station j within d_0 ($d_0 = 100$ km); (2) Calculate the neighboring haze ratio. For station j with haze, its neighboring haze ratio is $r(j) = m/M$, $(j = 1, \ldots, n)$, where M and m represent the number of neighboring stations and those with haze, respectively. $r(j)$ varies between 0 and 1. For station j without haze, $r(j)$ is defined as zero. (3) Select the daily centers of haze belts in the BTH region. Four conditions must be satisfied for the centers: (i) haze weather occurs at station j; (ii) $r(j) > R_0$, and $R_0 = 0.3$; (iii) the minimal distance (d_c) between each of the centers is greater than 150 km; (iv) the other stations with haze belong to the nearest center. (4) During an event process, any given day must have more than one center (an interruption of one day is allowed). (5) The duration should be three or more days. Note that some additional tests were carried out to determine suitable values for the major parameters such as d_0, d_c and R_0 in this study. The distance for neighboring stations (d_0) needs to be defined carefully to make sure every station has a moderate number of neighboring stations. d_c should be greater than d_0, and the ratio R_0 normally ranges between 0.3 and 0.5. It is also important to make sure that the results in extent and duration should be in accordance with the actual weather phenomena as far as possible.

An index (A_I) was used in this study to express the atmospheric thermal stability. The index was calculated using the following equation (Zhang et al., 2007):

$$A_I = (T_{850} - T_{500}) - [(T_{850} - T_{d850}) + (T_{700} - T_{d700}) + (T_{500} - T_{d500})] , \quad (1)$$

where T is the temperature and T_d is the dew-point temperature. The numbers 500, 700 and 850 indicate different pressure levels. The larger the value of A_I, the more unstable the atmosphere.

3. Circulation characteristics of the RPHEs in the BTH region

3.1. *Characteristics of the RPHEs*

The OITREE method is skillful at identifying RPHEs. About 49 RPHEs in the BTH region were identified from 1980 to 2013, and most of them occurred in autumn and winter (see Appendix). Among them, the RPHE of 14–25 December 2013 was the longest event recorded. As an illustrative example for severe and persistent haze events, Fig. 2a shows the distribution of the daily impacted areas of this RPHE. It can be seen that the regional haze event occurred mainly in the central and southern plain areas of the BTH region, which is in accordance with the spatial distribution of annual haze days in this region derived by Zhao et al. (2012) and Zhang et al. (2015). It is also clearly shown that the daily impacted areas changed on a daily basis. The regional haze first occurred in the southwest of Hebei Province and in Tianjin on 14 December and then expanded to the north of the BTH region. The extent of the haze event reduced on 18/19 December but developed again on 20 December. Until 25 December it covered almost the entire central and southern part of the whole region, before finally disappearing on 26 December. Visibility reduced significantly during this regional haze event. The mean visibility during the period was only around 6 km, but increased to nearly 14 km when the event ended on 26 December (figure not shown). Based on the above analysis, it can be seen that the OITREE method can objectively capture the daily impacted areas of an RPHE for its sustained period, and reasonably connect them in a "string" to shape an entire regional event (Ren et al., 2012).

During the 34-year study period, approximately 49% of the RPHEs in the BTH region lasted for three days, while 24% of them lasted for four days. RPHEs lasting for five or more days only accounted for 27% of the total (Fig. 3a). Among the identified RPHEs, the longest duration was 12 days. The occurrence frequency of RPHEs per year shows an increasing tendency (Fig. 3b), which is consistent with the rising trend in annual haze days in this region from 1980 to 2013 (Zhang et al., 2015). Before the mid-1980s, about 1.5 RPHEs occurred per year. Even fewer RPHEs occurred from the mid-1980s to the mid-1990s. However, since the mid-1990s, the occurrence frequency of RPHEs increased significantly to about 2.5 RPHEs per year. Of note is the occurrence of eight RPHEs in 2013 alone, which was the highest number in a single year recorded in the 34-year study period. This indicates a tendency of haze events in the BTH region towards longer durations and larger impact areas.

Thirteen severe RPHEs that lasted for five or more days were chosen for study (Table 1). Six of these events have been documented in the literature. Most of them occurred after 2005, which further suggests that the identification method of RPHEs used in this study is reasonable and effective. The fact that few RPHEs before 2005 have been documented is possibly because greater attention has been paid to air pollution in recent years.

In general, the occurrence of haze is not only related to increased pollutant emissions, but also to meteorological conditions that are unfavorable for the diffusion of pollutants (high relative humidity, weak surface wind and stability stratification, etc.). As these meteorological conditions are usually determined by the large-scale atmospheric circulation, we focused on these aspects of the above mentioned RPHEs in the BTH region (Table 1), as reported in the following sections.

3.2. *500 hPa geopotential height field*

The 13 RPHEs in the BTH region investigated here can be roughly categorized into two types according to their composite distributions of geopotential height at 500 hPa (Figs. 4a and b). For six haze events (numbers 1, 2, 4, 7, 8, and 11 in Table 1), East Asia was mainly dominated by a zonal circulation in the mid-level of 500 hPa, and the BTH region was controlled by zonal westerly airflow, indicating less cold and dry air intrusion from high latitudes into the region. Such RPHEs under this specific atmospheric circulation were categorized as zonal westerly airflow (ZWA)-type RPHEs. For the other seven haze events (numbers 3, 5, 6, 9, 10, 12, and 13 in Table 1), mainland China was dominated by a weak

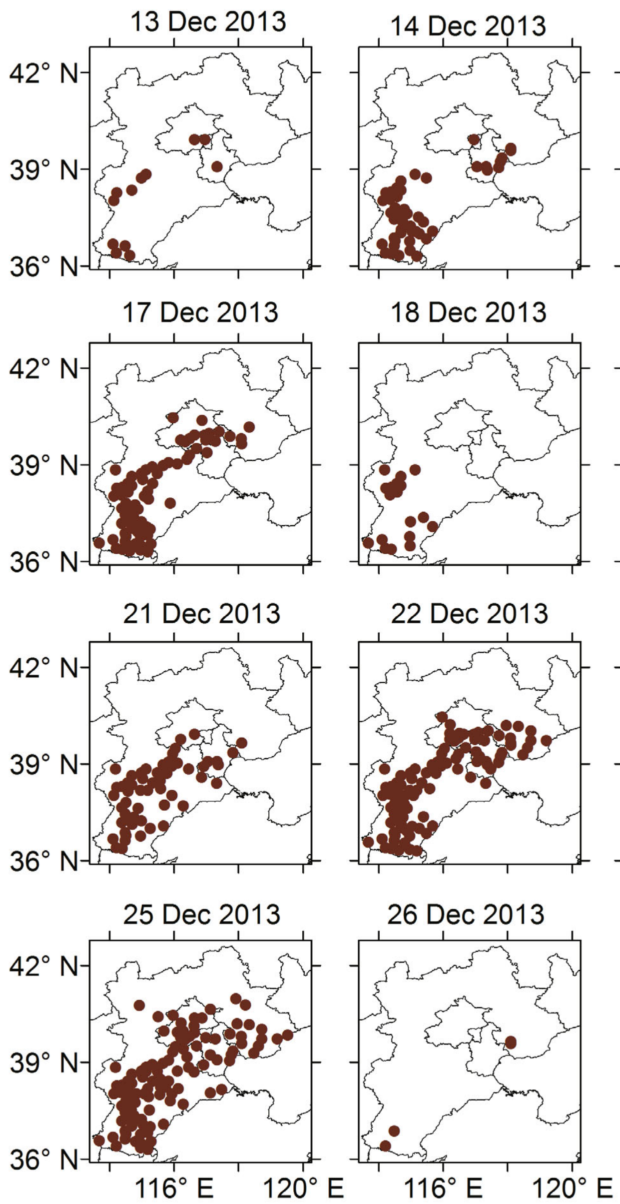

Fig. 2. Evolution of the daily impacted areas of the RPHE from 14 to 25 December 2013 in the BTH region (dots represent the stations with haze).

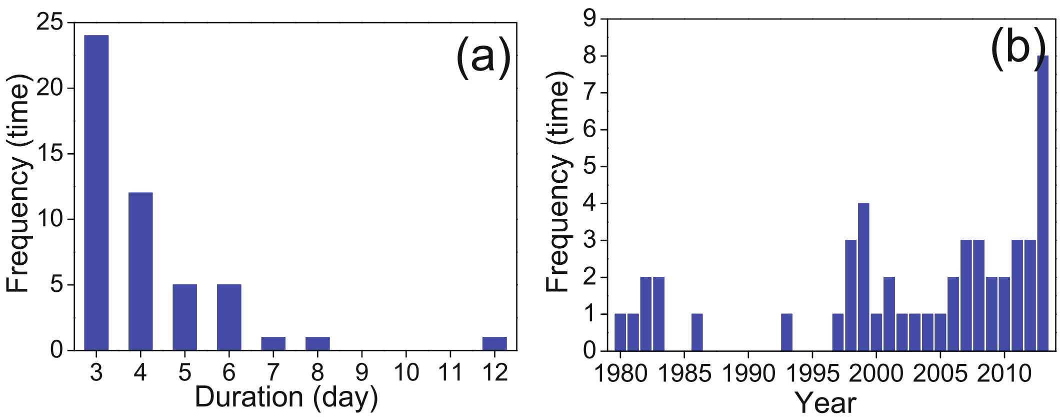

Fig. 3. Frequency distributions for the duration (a) and the long-term variation of the frequency of the RPHEs (b) in the BTH region from 1980 to 2013.

Table 1. RPHEs in the BTH region that lasted for five or more days from 1980 to 2013.

Number	Start and end time (year/month/day)	Duration (d)	Literature record
1	1998/12/17–1998/12/22	6	–
2	1999/12/26–1999/12/30	5	–
3	2004/10/6–2004/10/10	5	–
4	2005/11/1–2005/11/5	5	Haze pollution occurred in Beijing from 2 to 5 November 2005 (Wu and Zhang, 2010)
5	2006/1/20–2006/1/27	8	–
6	2007/2/16–2007/2/21	6	–
7	2009/11/4–2009/11/8	5	Haze pollution occurred in Beijing from 3 to 8 November 2009 (Cao et al., 2013)
8	2011/2/19–2011/2/24	6	Haze pollution occurred in Beijing from 18 to 24 February 2011 (Jin et al., 2012)
9	2013/1/6–2013/1/12	7	Haze pollution occurred in North China from 10 to 14 January 2013 (Tang et al., 2013) Haze pollution occurred in the BTH region from 9 to 17 January 2013 (Liu et al., 2015)
10	2013/2/24–2013/2/28	5	Haze pollution occurred in Beijing from 23 to 28 February 2013 (Liao et al., 2014) Haze pollution occurred in Tianjin from 20 to 28 February 2013 (Liu and Wang, 2015)
11	2013/10/4–2013/10/9	6	Haze pollution occurred in the North China in October 2013 (Wang, 2013)
12	2013/12/2–2013/12/7	6	–
13	2013/12/14–2013/12/25	12	–

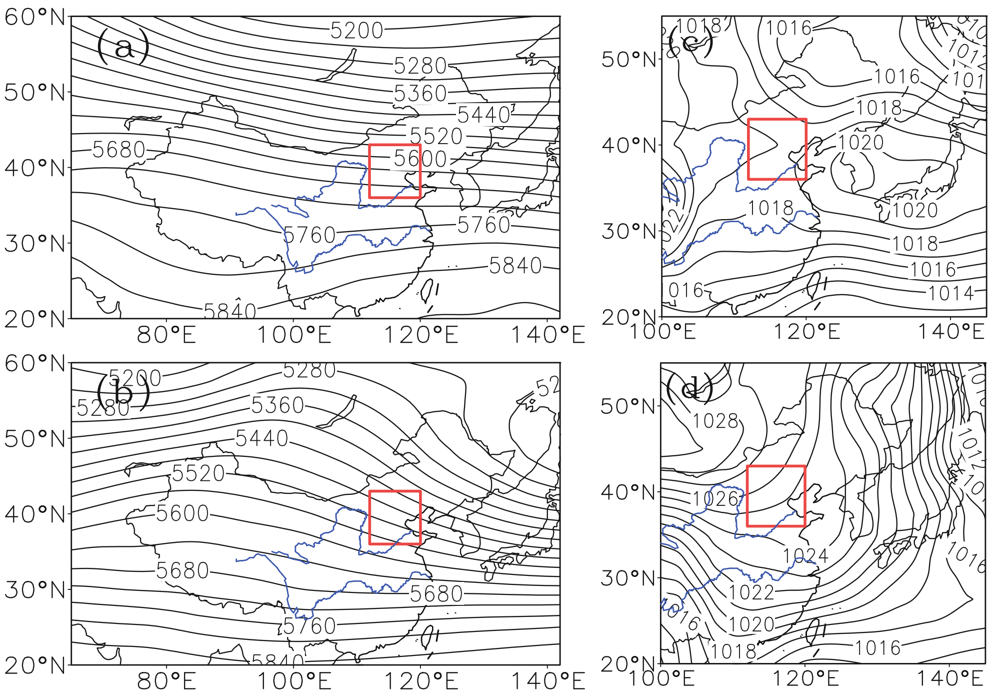

Fig. 4. Composite distributions of 500 hPa geopotential height (a, b; units: gpm) and sea level pressure (c, d; units: gpm) for the two types of RPHEs: (a, c) ZWA-type RPHEs; (b, d) HPR-type RPHEs. Rectangular region represents the BTH region.

high pressure ridge, and the BTH region was controlled by northwesterly airflow in front of this ridge. Such RPHEs under this specific atmospheric circulation were categorized as high pressure ridge (HPR)-type RPHEs. Moreover, the same two types could also be categorized according to the systems in the lower–mid troposphere (700 hPa and 850 hPa).

When a ZWA-type RPHE occurred, the BTH region was dominated by a uniform pressure field in the rear of the high pressure system at the surface (Fig. 4c), whereas the BTH region was dominated by a uniform pressure field in front of the high pressure system when an HPR-type RPHE occurred (Fig. 4d). Compared with the ZWA-type RPHEs, the sea level pressure of the HPR-type RPHEs was a bit stronger. Furthermore, the surface pressure gradient decreased with the occurrence of both types of RPHEs (figure not shown). The uniform pressure field and the weak surface pressure gradient at the surface of the two types of RPHEs resulted in weak surface wind speeds, which contributed to the formation and maintenance of haze.

3.3. *Wind conditions*

The concentration of haze nuclei depends on wind and humidity. Wind is related to the dispersion and transportation of air pollutants, while humidity is linked to the hygroscopicity and scattering of particles (Wang et al., 2014a). Figure 5 presents the composite distributions of wind vectors at 850 hPa and 925 hPa. When a ZWA-type RPHE occurred, westerly or southwesterly winds prevailed at 850 hPa over the BTH region with wind speeds in most areas ranging between 3 to 7 m s^{-1} (Fig. 5a). At 925 hPa, mainly southwesterly winds prevailed, with lower wind speeds of 2 to 4 m s^{-1} (Fig. 5c). Due to the effect of the southwesterly winds, a large amount of air pollutants from the surrounding areas such as Shanxi Province and Henan Province were easily transported into the region. The Yanshan Mountains are located to the north of the BTH region and act as a barrier, hindering the northward dispersion of pollutants. Meanwhile, the southwesterly winds contributed to the transportation of warm and humid moisture into this region, and provided favorable material and moisture conditions for the occurrence of a haze event.

Different from the ZAW-type RPHEs, when an HPR-type RPHE occurred, northwesterly and westerly winds prevailed over the BTH region at 850 hPa and 925 hPa, respectively (Figs. 5b and d). The wind speeds were similar to those that occurred during ZAW-type RPHEs. Note that a meridional southerly wind component prevailed at 925 hPa (figure not shown), implying that the northwesterly airflow mainly influenced this region in the middle troposphere but did not reach the surface, indicating that the cold air from the upper levels had less of an effect at the surface. This situation is basically consistent with the results of the two typical haze examples analyzed by Liao et al. (2014, 2015). Accordingly, the weak westerly and southerly winds at the near-surface might transport air pollutants from Shanxi Province to this region, thus leading to an increase in the concentration of air pollutants.

We also calculated the surface wind speeds (Figs. 5e and f) and found that, regardless of which type of RPHE occurred, the wind speeds in most areas were very low (only 1–2 m s^{-1}), which was unfavorable for the diffusion of air pollutants but conducive to the accumulation of pollutants on a regional scale. The lower wind speeds were mainly found in the transition region between mountains and plains, where the most serious air pollution over the BTH region is generally detected. Hence, southwesterly or westerly winds in the lower troposphere might be conducive to the accumulation of air pollutants, and the weak surface winds might weaken the dispersion of pollutants.

3.4. *Humidity conditions*

Humidity is an important factor in the formation of haze events due to the hygroscopic growth of haze particles. Figure 6 shows the characteristics of the water vapor transport at 850 hPa and 925 hPa for the two types of RPHEs. When a ZWA-type RPHE occurred, anticyclonic circulation was situated over eastern China and the northwestern Pacific. Warm and humid airflows originated from the northwestern Pacific were transported into the BTH region through the southeastern coastal areas of China at 850 hPa and 925 hPa (Figs. 6a and c), creating favorable moisture conditions for the development of haze. However, when an HPR-type RPHE occurred, the BTH region was mainly influenced by dry and cold northwesterly and westerly water vapor at 850 hPa and 925 hPa (Figs. 6b and d). The moisture conditions for the haze events were relatively weak. In addition, the BTH region was controlled by moisture convergence in the mid–lower troposphere for both types of RPHEs, benefiting the development of haze in this region.

Figures 6e and f show the surface relative humidity in the BTH region for the two types of RPHEs. Due to the blocking of the Yanshan and Taihang mountains, moisture is transported solely into the piedmont plains, resulting in wetness

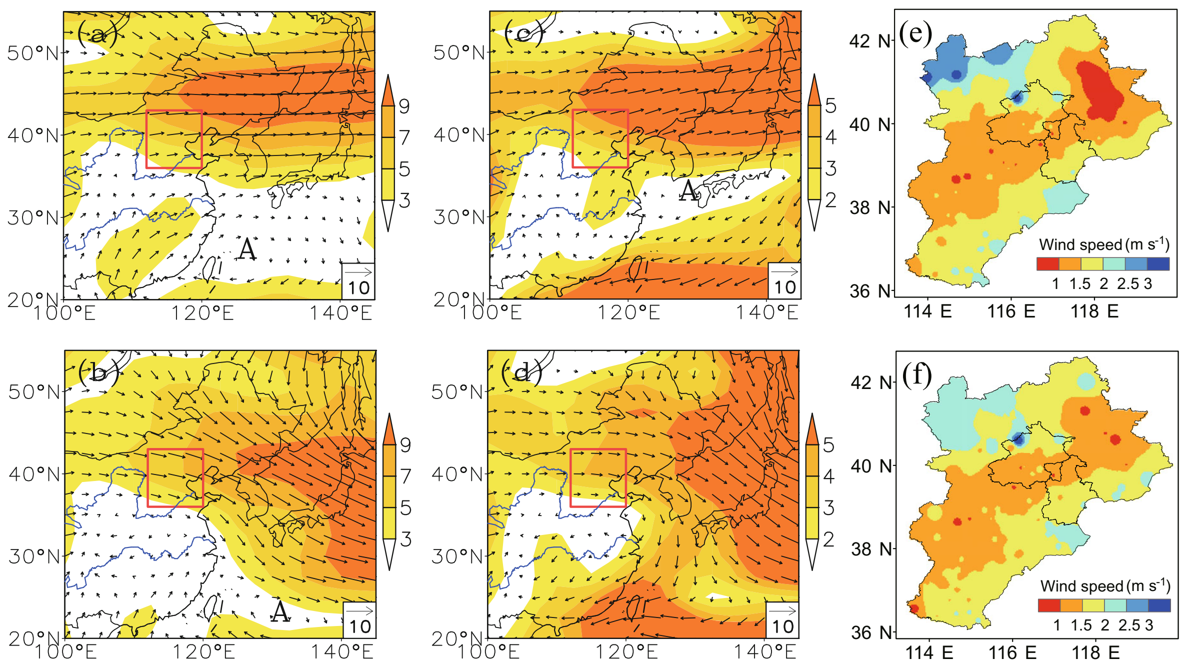

Fig. 5. Composite distributions of wind vectors and wind speeds (shading) at (a, b) 850 hPa and (c, d) 925 hPa (units: m s^{-1}), and (e, f) near-surface wind speed (units: m s^{-1}) for the two types of RPHEs, respectively: (a, c, e) ZWA-type RPHEs; (b, d, f) HPR-type RPHEs. Rectangular region represents the BTH region.

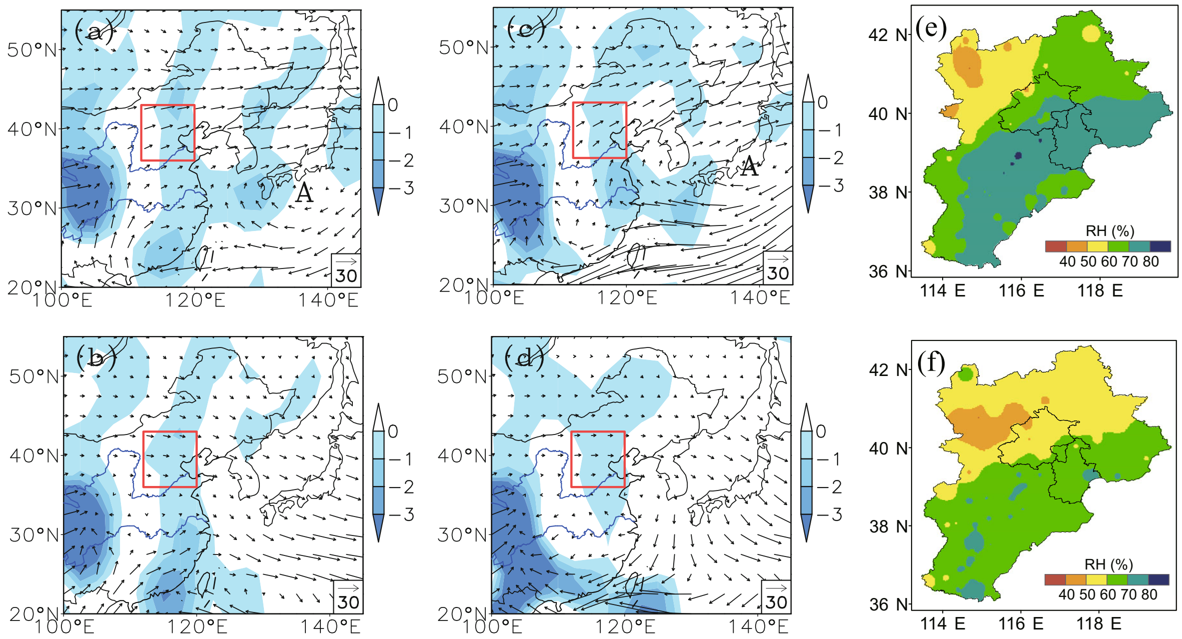

Fig. 6. Composite distributions of water vapor transport [vectors; units: 10^{-1} g (hPa cm s)$^{-1}$] and vapor flux divergence [shading; units: 10^{-6} g (hPa cm^2 s)$^{-1}$] at (a, b) 850 hPa and (c, d) 925 hPa, and (e, f) near-surface relative humidity, for the two types of RPHEs: (a, c, e) ZWA-type RPHEs; (b, d, f) HPR-type RPHEs. Rectangular region represents the BTH region.

over the southern plain areas but dryness over the northern mountainous areas. When a ZWA-type RPHE occurred, the relative humidity over the plain areas was 70%–80%. The relative humidity for the HPR-type RPHEs, however, was only 60%–70%. The difference in relative humidity between the two types of RPHEs might be caused by their important local circulation of the convergence of moisture, and might also be affected by their different moisture sources and pathways.

4. Dynamic mechanism

In addition to horizontal motion, vertical motion is also an important dynamic factor for the development of haze, as it has a great effect on the vertical dispersion of pollutants (Zhao et al., 2013). Li et al. (2012) found that the boundary layer was controlled by descending movement when the haze event of 23–29 November 2009 in Guangzhou occurred, which could have suppressed the vertical transportation of pollutants. Liao et al. (2015) found that vertical motion showed an ascending–descending–ascending distribution from the surface to the middle troposphere when a haze event occurred from 13 to 15 March 2013 in Beijing. Correspondingly, the wind conditions displayed a convergence–divergence–convergence structure. The vertical wind and vertical velocity conditions were conducive to the accumulation of contaminants in a shallow layer and prevented them from diffusing into the upper layers. Figure 7 depicts the composite pressure–latitude profiles of wind divergence and vertical velocity of the two types of RPHEs. For the ZWA-type RPHEs, the wind presented the above-mentioned three-layer vertical structure, i.e., a shallow convergence at 1000–950 hPa, followed by a divergence at 950–700 hPa, and a convergence at 700–500 hPa (Fig. 7a). According to the continuous theorem of quality, the observed vertical distribution can lead to a haze-benefiting sinking motion. It can be seen in Fig. 7c that the BTH region was completely controlled by a sinking motion in the mid–lower troposphere. For the HPR-type RPHEs, similar vertical distributions of wind and vertical motion were found (Figs. 7b and d). However, the intensity of the vertical sinking motion was stronger compared to the ZWA-type RPHEs.

Next, the profiles of wind divergence and vertical velocity of the 13 RPHEs were analyzed (Fig. 8). It can be seen that the wind showed the above-mentioned structure of a convergence below 925 hPa, a divergence at 925–700 hPa, and a convergence again at 700–500 hPa, for most of the RPHEs. For three of these RPHEs (19–25 February 2011; 4–9 October 2013; 24–28 February 2013), the BTH region was controlled by an ascending motion below 925 hPa but by sinking motion at 925–500 hPa, as deduced from the vertical velocity distribution, which is similar to the vertical structure analyzed by Liao et al. (2015). However, when the other 10 RPHEs occurred, the BTH region was almost completely controlled by sinking motion at 1000–500 hPa. Moreover, the temperature increased in the mid–lower troposphere (Figs. 8e and f), and the inversion layer was found below 925 hPa or 850 hPa for most of the RPHEs according to real-time monitoring, which suggested that the atmosphere was relatively stable. Sinking motion and inversion usually weaken the vertical dispersion of pollutants, which may further lead to the long-term maintenance of a haze event.

From another perspective, sinking motion in the mid–lower troposphere can affect the PBL height by compressing the air mass. As the effective air volume of the pollutants' diffusion is determined by the PBL thickness (Zhang et al., 2012), the evolution of the PBL has a significant effect on

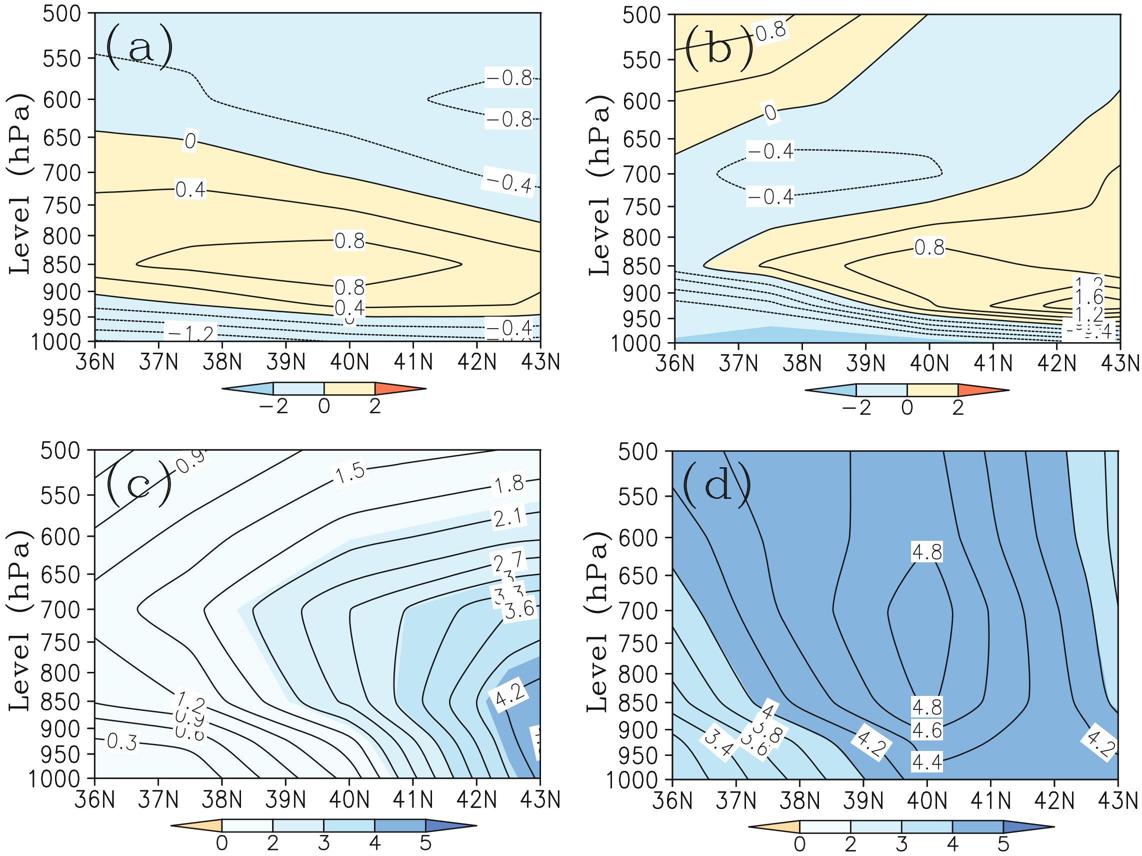

Fig. 7. Composite pressure–latitude profiles of (a, b) wind divergence (units: 10^{-6} s^{-1}) and (c, d) vertical velocity (units: 10^{-2} Pa s^{-1}) for the two types of RPHEs: (a, c) ZWA-type RPHEs; (b, d) HPR-type RPHEs.

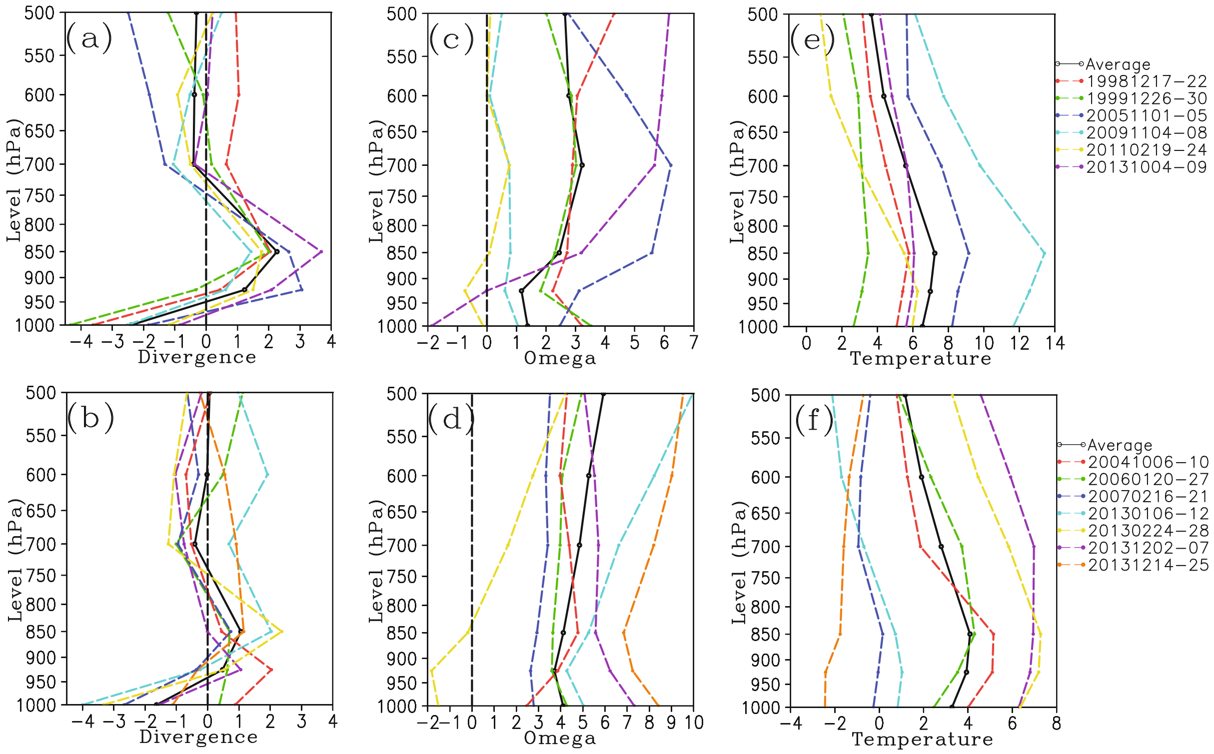

Fig. 8. Vertical distribution of (a, b) wind divergence (units: 10^{-6} s^{-1}), (c, d) vertical velocity (units: 10^{-2} Pa s^{-1}) and (e, f) temperature anomaly (units: °C) of the 13 RPHEs: (a, c, e) ZWA-type RPHEs; (b, d, f) HPR-type RPHEs.

air pollution (Han et al., 2009; Quan et al., 2013). A lower PBL height and strong inversion or stable layer at the top of the PBL can cut off the air flow between the upper and lower layers (Zhao et al., 2013). As depicted in Fig. 9a, the PBL heights of most of the RPHEs were lower than average. The average PBL height of the observed RPHEs was about 820 m, which was about 100 m lower than the monthly mean. An exception was the RPHE that occurred in 1998, which was due to the restrictions of the FNL reanalysis dataset length. This generally indicates a potential accumulation of more aerosol particles in the lower PBL, which would increase the concentration of pollutants. Additionally, the $A_{\rm I}$ reduced significantly with the occurrence of most RPHEs (Fig. 9b), suggesting a relatively stable atmosphere. The formation of a stable atmosphere might be due to the inversion in the lower troposphere caused by the sinking motion. Because of the lower PBL height and the steady atmospheric stratification, the ability of pollutants to disperse vertically might decrease. Thus, more pollutants and moisture might be constrained to the lower PBL, benefiting the maintenance and aggravation of haze.

As described above, the two types of RPHEs generally result from the effects of both the atmospheric circulation and the sinking motion. A schematic representation of the formation of RPHEs in the BTH region is shown in Fig. 10. It can be seen that when a ZWA-type RPHE occurs, westerly winds prevail in the middle troposphere and weak southwesterly winds prevail in the PBL, with good moisture conditions. Whereas, when an HPR-type RPHE occurs, northwesterly winds prevail in the middle troposphere and weak westerly winds prevail in the PBL, with relatively weak moisture conditions. Also, the occurrence of divergence sinking motion in the mid–lower troposphere may lower the PBL height by compressing the air, and then the local and other pollutants from surrounding provinces will be confined into the relatively low PBL height. In addition, the sinking motion may

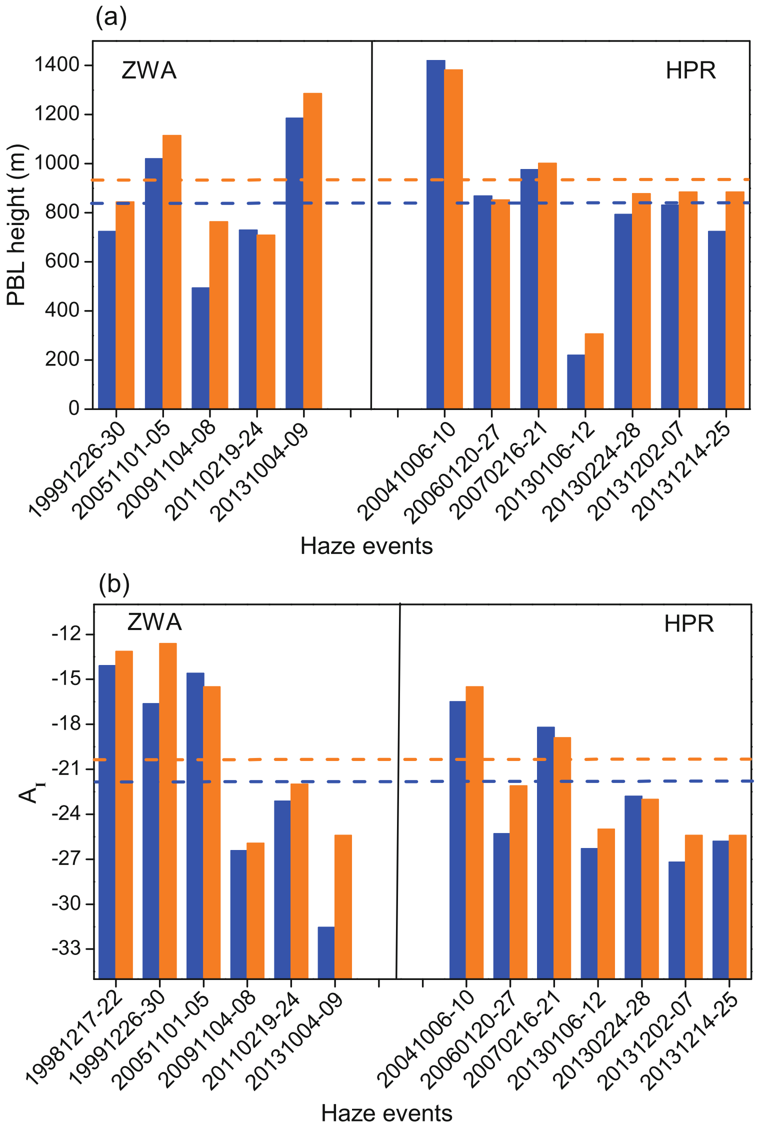

Fig. 9. The (a) PBL height (units: m) and (b) A_I (blue columns represent the PBL height or A_I when the 13 RPHEs occurred; yellow columns represent the monthly mean values in which month the 13 RPHEs occurred).

generate inversion in the lower troposphere, leading to an increase in atmospheric stability when the zonal westerly airflow crosses over the Taihang Mountains or the northwesterly airflow crosses over the Yanshan Mountains. The atmospheric inversion may restrain the exchange of air mass between the PBL and the free atmosphere. It is worth noting that the convergence layer, which is located above the divergence layer, plays an important role in the formation of the sinking motion. If the above-mentioned situation remains in place for a long time, the haze event will be continuously maintained and further exacerbated.

5. Conclusions

In recent decades, the BTH region has suffered from severe and persistent haze events. Frequently occurring air pollution has become a very serious environmental problem. In this study, RPHEs in the BTH region were identified using the OITREE method from 1980 to 2013. The formation mechanisms of the severe RPHEs were analyzed with respect to the atmospheric circulation and dynamical conditions. The following conclusions can be drawn:

(1) Forty-nine RPHEs occurred in the BTH region in the 34-year study period. The occurrence frequency of the RPHEs showed an increasing tendency. Most of the RPHEs lasted for 3–4 days, with the longest duration being 12 days.

(2) The most severe RPHEs in the BTH region could be categorized into ZWA-type and HPR-type RPHEs based on their associated large-scale circulation characteristics. When a ZWA-type RPHE occurred, the BTH region was controlled by zonal westerly airflow in the mid–upper troposphere and a uniform pressure field at the surface, suggesting that weak cold air activity might have affected the region. Southwesterly winds prevailed in the lower troposphere, which might have transported pollutants from the surrounding areas and sufficient moisture from the south into the region. The near-surface wind speeds of only 1–2 m s^{-1} weakened the horizontal dispersion of air pollutants and the high near-surface relative humidity of about 70%–80% facilitated the hygroscopic growth of haze particles, creating favorable conditions for the RPHEs to occur and be maintained.

(3) When an HPR-type RPHE occurred, the BTH region was controlled by northwesterly airflow in the mid–upper troposphere, with cold air activity in the upper level having little effect on the surface. Westerly winds prevailed in the lower troposphere and the moisture conditions were relatively weak for the occurrence of haze events.

(4) The above two circulation patterns of RPHEs can produce strong and persistent sinking motion in the mid–lower troposphere in the BTH region. Therefore, sinking motion might be a very important dynamic factor for the formation and development of these two types of RPHEs. Downward airflow is favorable for reducing the PBL height and forming a temperature inversion, which causes air pollutants and moisture to progressively accumulate in the lower PBL. The lower PBL might significantly decrease the potential atmospheric capacity for the diffusion of air pollutants, leading to high concentrations of pollutants in the BTH region. The convergence layer, which is located above the divergence layer, contributes a great deal to the formation of such sinking motion in a deep layer under the ZWA and HPR circulation patterns.

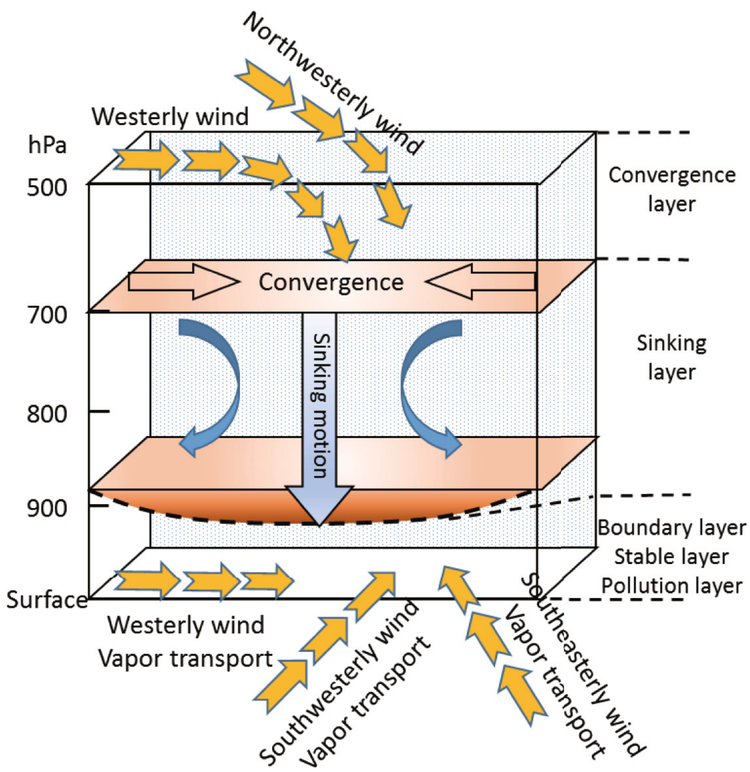

Fig. 10. Schematic representation of the formation mechanism for RPHEs in the BTH region.

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APPENDIX

RPHEs in the BTH region from 1980 to 2013 identified by the OTTREE method

Number	Start and end time (year/month/day)	Duration (d)
1	1980/2/22–1980/2/24	3
2	1981/12/25–1981/12/27	3
3	1982/1/1–1982/1/4	4
4	1982/12/8–1982/12/10	3
5	1983/1/2–1983/1/4	3
6	1983/1/26–1983/1/29	4
7	1986/1/17–1986/01/19	3
8	1993/10/7–1993/10/9	3
9	1997/1/10–1997/1/12	3
10	1998/3/2–1998/3/5	3
11	1998/3/25–1998/3/28	4
12	1998/12/17–1998/12/22	6
13	1999/1/22–1999/1/24	3
14	1999/3/23–1999/3/25	3
15	1999/11/20–1999/11/22	3
16	1999/12/26–1999/12/30	5
17	2000/3/11–2000/3/14	4
18	2001/6/8–2001/6/10	3
19	2001/10/20–2001/10/23	4
20	2002/10/9–2002/10/11	3
21	2003/6/18–2003/6/20	3
22	2004/10/6–2004/10/10	5
23	2005/11/1–2005/11/5	5
24	2006/1/20–2006/1/27	8
25	2006/12/19–2006/12/21	3
26	2007/1/14–2007/1/16	3
27	2007/2/16–2007/2/21	6
28	2007/11/5–2007/11/7	3
29	2008/1/5–2008/1/8	4
30	2008/3/9–2008/3/12	4
31	2008/12/8–2008/12/10	3
32	2009/2/3–2009/2/6	4
33	2009/11/4–2009/11/8	5
34	2010/7/26–2010/7/29	4
35	2011/1/19–2011/1/22	4
36	2011/2/19–2011/2/24	6
37	2011/12/26–2011/12/28	3
38	2012/1/14–2012/1/16	3
39	2012/2/21–2012/2/23	3
40	2012/11/24–2012/11/26	3
41	2013/1/6–2013/1/12	7
42	2013/2/24–2013/2/28	5
43	2013/3/6–2013/3/9	4
44	2013/3/15–2013/3/17	3
45	2013/6/15–2013/6/18	4
46	2013/10/4–2013/10/9	6
47	2013/11/20–2013/11/23	4
48	2013/12/2–2013/12/7	6
49	2013/12/14–2013/12/25	12

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